Inflammation is the main risk factor of voriconazole overdose in hematological patients

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Running title: inflammation and voriconazole overdose

Abstract

Aim: Voriconazole (VRC) overdoses are frequent and expose patients at high risk of adverse effects. This case-control study performed in hematological patients who benefited from VRC therapeutic drug monitoring from January 2012 to December 2015 aimed to identify risk factors of VRC overdose.

Methods: Pharmacogenetic, biological, and demographic parameters at the time of VRC trough concentration (Cmin) were retrospectively collected from medical records. Cases (VRC overdose: defined by a VRC Cmin $\geq$ 4 mg/l; n = 31) were compared to controls (no VRC overdose: defined by VRC Cmin < 4 mg/L; n = 31) using non-parametric or Chi-square tests followed by multivariable analysis.

Results: VRC overdoses were significantly associated with high CRP and bilirubin levels, intra-venous administration, and age in univariable analysis. In contrast, the proportion of CYP genotypes (CYP2C19, CYP3A4, or CYP3A5, considered alone or combined in a genetic score¹) were not significantly different between patients who experienced a VRC overdose and those who did not. In multivariable analysis, the class of CRP level (defined by median CRP levels of 96 mg/l) was the sole independent risk factor of VRC overdose (p < 0.01). Patients with CRP levels > 96 mg/l had a 27-fold (IC 95%: [6-106]) higher risk of VRC overdose than patients with CRP levels $\leq$ 96 mg/l.

Conclusion: This study demonstrates that inflammatory status, assessed by CRP levels, is the main risk factor of VRC overdose in French hematological patients, whereas pharmacogenetic determinants do not appear to be involved.

Key-words: voriconazole, inflammation, therapeutic drug monitoring, pharmacogenetics.

¹ Gautier-Veyret et al., AAC 2015

Introduction

Invasive fungal infections (IFI) are a major concern in immunocompromised patients. Among them, invasive aspergillosis (IA) is particularly feared in hematological units, as mortality occurs in 19 to 61% of cases (1). The management of antifungal therapy of IA is challenging due to various issues inherent either to inadequate exposure or drug safety. The first-line treatment of IA, voriconazole (VRC), is notably concerned by such issues, as this drug exhibits both highly variable pharmacokinetics and a narrow therapeutic range (2). Thus, VRC therapeutic drug monitoring (TDM) is recommended to optimize treatment (2, 3), as VRC trough concentrations (C_{min}) are associated with both efficacy and toxicity (4).

Despite TDM, VRC C_{min} are frequently out-of-the therapeutic range in clinical practice. Indeed, subtherapeutic VRC C_{min} have been found in 20 to 33% of patients (5, 6) and supratherapeutic VRC C_{min} in 8.8 to 23% of cases (5–7), depending on the therapeutic threshold and study population. Although subtherapeutic VRC C_{min} are often explained by gain-of-function single nucleotide polymorphism (SNP) *17 for CYP2C19 (at least in the Caucasian population) (8–11), comedication by enzymatic inducers (12), or non-observance (9), the determinants of supratherapeutic VRC C_{min} have been less investigated. Numerous factors, such as liver dysfunction, the use of enzymatic inhibitors (13), the presence of loss-of-function SNPs for CYP2C19 (14), and inflammation (15, 16), have already been identified to be associated with increased VRC C_{min}, but their impact on the occurrence of VRC overdose has never been investigated. This issue is all the more relevant as 1) the magnitude of the effect of each individual factor on VRC C_{min} appears to be relatively weak (4) and 2) some of these factors, such as inflammation and genetic variants of CYP2C19, may be linked (17–19) and interact (15, 16). Here, we aimed to identify risk factors associated with VRC overdose in a cohort of hematological patients treated by VRC followed by TDM.

Materials and methods

Study design

This retrospective case-control study was conducted at Grenoble Alps University Hospital, France in a hematological unit. Adult patients (> 18 years old) who experienced a VRC overdose, defined by VRC C_{min} determined at steady-state ≥ 4 mg/l (2) between January 2012 and December 2015 were eligible. Patients were excluded in cases of prescription error, missing data, sampling before pharmacokinetic steady state, suspicion of non-observance, unavailability of their DNA and also if they were < 18 years (see Figure 1 for details).

Risk factors of VRC overdose were assessed by comparing patients experiencing VRC overdose to control patients (those with therapeutic VRC C_{min} between 1 and 4 mg/l), who were randomly included among all patients being followed by VRC TDM during the same period. The inclusion and non-inclusion criteria for the selection of controls were similar to those for patients who experienced a VRC overdose, except for the VRC C_{min}.

Demographic, clinical (underlying disease, hematopoietic stem cell transplantation), biological (CRP, ALAT, Bilirubin, VRC C_{min}), and pharmaceutical data (VRC daily dose, route of administration, comedication with pump proton inhibitors (PPIs)) were retrospectively collected from medical records. If several VRC overdose episodes occurred for one patient, only the first was considered. The inflammatory status was assessed by determining the CRP level the same day as determination of the VRC C_{min}. The absence of a strong enzymatic inducer or inhibitor was verified.

Ethics statement

Informed written consent was obtained for all patients for genetic analysis, sample collection, and use of their data, in accordance with the Declaration of Helsinki. The study and biobank were approved by the IRB 6705 (CPP Sud Est 5, Grenoble, France).

Therapeutic drug monitoring

Plasma VRC Cmin were determined at steady state for samples handled just before VRC administration using a validated liquid chromatography-tandem mass spectrometry (20).

Genotyping and determination of the combined genetic score

Genotyping of CYP2C19 and CYP3A was performed on residual samples taken before allograft and stored in a biological sample collection (CRD-2013-1983). Only residual samples taken before allograft were considered for hematopoietic stem cell allograft recipients. The presence of CYP2C19*2 (rs4244285), CYP2C19*17 (rs72558186), CYP3A5*3 (rs776746), and CYP3A4*22 (rs35599367) was investigated using the TaqMan allelic discrimination assay (Life Technologies, Illkirch, France). The phenotype of CYP2C19 was defined according to the Clinical Pharmacogenetics Implementation Consortium (CPIC) guidelines for CYP2C19 and voriconazole (21). In addition, a genetic score, integrating both CYP2C19 and CYP3A genotypes, was determined for each patient according to our previous studies (11, 22): the higher the genetic score, the faster the metabolism of the patient. The Hardy-Weinberg equilibrium was tested for each polymorphism by the online method of Rodriguez *et al.* (23).

Statistical analysis

Quantitative data are expressed as medians (25th -75th percentiles). The link between VRC overdose and potential risk factors was investigated either by comparing the distribution of qualitative data (sex, cotreatment by PPI, route of administration, class of CRP based on a median CRP level of 96 mg/L, phenotype of CYP2C19, etc.) with either a Chi-square or Fisher's exact test by comparing the values of continuous data (VRC dosing, CRP levels) by the Man-Whitney test. A multivariable logistic regression model was performed to account for potential confounders. CRP was categorized into two classes due to the absence of log-linearity: CRP $\leq$ or $>$ 96 mg/l, based on the median. Variables with a p value threshold of 0.2 in univariable analysis were selected and introduced in the multivariable analysis, except in cases of collinearity. A stepwise procedure was used to select the final model.

Statistical analyses were performed using SAS v9.4 (SAS Institute Inc., Cary, NC). Significance was considered for $p < 0.05$.

Results

Baseline characteristics of patients and potential risk factors are described in Table 1. Thirty-one patients, who experienced a VRC overdose, as well as thirty-one controls without a toxic VRC Cmin, were included. The median for the VRC Cmin in the cases (patients who experienced a VRC overdose) was 5.3 mg/l *versus* 1.0 mg/l for the control group (Table 1).

In univariable analysis, patients in the case group were older, exhibited higher bilirubin levels, and were more frequently treated by intravenous voriconazole than those in the control group (Table 1). The proportion of allografted patients was lower in the case than control group. In addition, the distribution of CRP levels was significantly different between patients who experienced a VRC overdose and those who did not (table 1), with higher CRP levels for cases than controls (Figure 2).

In contrast, VRC dose, sex, weight, PPI treatment, ALAT levels, underlying disease, and pharmacogenetic parameters were not associated with a risk of VRC overdose, except for the distribution of the CYP2C19 phenotype (table 1) or diplotype (Table E1), which tended to differ between patients who experienced a VRC overdose and those that did not ($p = 0.07$ and $p = 0.1$, respectively). There was no association between pharmacogenetic parameters and risk of VRC overdose, either when cytochromes CYP2C19, CYP3A4, or CYP3A5 were considered alone or evaluated in the combined genetic score (table 1).

We investigated a possible link between CRP levels and pharmacogenetic parameters (17–19) by comparing CRP levels (considered as continuous variables or CRP classes) according to CYP2C19 phenotype and combined genetic score class. There was no difference in CRP levels depending on either CYP2C19 phenotype or combined genetic score class (Figure E1 and Table E2).

In the multivariable analysis, only the class of CRP level was significantly and independently associated with VRC overdose ($p < 0.01$). Patients with a CRP > 96 mg/l had a greater risk of VRC overdose than patients with a CRP ≤ 96 mg/l (odds ratio (95 % confidence interval): 27 [6-106]).

Discussion

This study identified, for the first-time, inflammation (assessed by CRP levels) to be a strong independent risk factor of VRC overdose in hematological patients. These data suggest that hematological patients may be at increased risk of supratherapeutic VRC C_{min} and associated toxicity when they exhibit increased CRP levels, which is very frequent for patients with IA (24, 25).

Such an elevated CRP-level associated risk of VRC overdose is in accordance with several previous studies reporting positive associations between elevated CRP levels and high VRC C_{min} (15, 16, 26–28). This is probably related to inflammation-induced phenoconversion, during which proinflammatory cytokines, such as interleukin-6, reduce both CYP3A4 and CYP2C19 expression and activity (29). Hence, it is probable that inflammation rapidly inhibits VRC metabolism by reducing CYP3A4 and CYP2C19 activities, which ultimately results in increased VRC C_{min} and greater risk of overdose.

PPI cotreatment, advanced age, and high bilirubin levels, which have already been reported to be associated with increased VRC C_{min}, were not associated (PPI treatment) or only associated in univariable analysis (age and hepatic dysfunction) with a risk of VRC overdose in this study. Similarly, none of the pharmacogenetic parameters, including the CYP2C19 phenotype or the CYP3A4 and CYP3A5 genotypes, considered alone or in a combined genetic score, were associated with VRC overdose. This result is surprising, as numerous previous studies have demonstrated that the loss-of-function SNPs affecting CYP2C19 (*2 or *3) (30–32) or CYP3A4 (*22) (11, 33–36) were associated with elevated VRC C_{min}. These discrepancies may be explained by the relatively low number of patients included, which limited the statistical power of our study and increased the width of the

confidence intervals. Despite this limitation, our work clearly demonstrates that inflammation, shown by high CRP levels, is the sole independent risk factor of VRC overdose in French hematological patients, completely masking the effects of other potential risk factors.

In addition, we investigated the possible link between CRP levels and the CYP2C19 phenotype by additional statistical analyses (see Table E2 and Figure E1 in supplemental data). Although there was no association between CRP and pharmacogenetic parameters (both CYP2C19 phenotype and class of combined genetic score), the absence of a link cannot be completely ruled out as CRP and IL-6 levels have been reported to be elevated in poor CYP2C19 metabolizers (17–19). These findings suggest that an association between loss-of-function SNPs of CYP2C19 and elevated VRC Cmin (8, 30, 37) could result in reduced VRC metabolism due to diminished CYP2C19 activity (direct effect), as well as an increase in IL-6 levels, and hence down-regulation of CYP2C19 and CYP3A4 activities (indirect effect). Further studies should be performed to clarify the respective roles of inflammation and pharmacogenetic determinants on VRC Cmin and explore their eventual link, especially as the effect of inflammation on VRC Cmin may be modulated by pharmacogenomic parameters (15, 38).

This study had several limitations. First, it was retrospective, performed in a single center, and only a small number of subjects was included. Second, data on the clinical consequences of VRC overdose in terms of side effects, treatment discontinuation, and efficacy of treatment was absent. This aspect may be particularly important to explore in the future, as studies have already shown that elevated pro-inflammatory cytokine levels are a predictor of poor outcome in invasive aspergillosis (24, 25).

In conclusion, our study identified inflammation as the main risk factor of VRC overdose in French hematological patients, whereas pharmacogenetic determinants do not appear to be involved. Hence, the inflammatory status, evaluated by CRP levels, must be assessed for every VRC overdose and individualized dose adjustments will probably need to be integrated during the longitudinal evolution of inflammation (26, 39) to obtain a VRC Cmin within the therapeutic range. In the era of individualized VRC therapy based on CYP2C19 phenotype (21), a more global approach may be of

195 interest to effectively and rapidly individualize VRC therapy, taking into account not only the
 196 CYP2C19 phenotype (21), but also other determinants of VRC Cmin, particularly SNPs affecting other
 197 enzymes involved in VRC metabolism, such as CYP3A4 (11, 33–36), eventual comedication by
 198 enzymatic inhibitors/inducers (11, 40) and, of course, inflammatory status (15, 16, 26–28).

199

200 **Acknowledgments**

201 The authors thank Christel Roche and Mélanie Davallet-Pin, Cécile Pistone-Girard and Karine
202 Scalabrino for their excellent technical assistance.

203 **Conflict of interest:** none

204 **Funding**

205 This research received no specific grant from any funding agency in the public, commercial, or not-
206 for-profit sectors.

207 **Figure legends**

208 Figure 1. Flow chart

209 VRC, voriconazole; TDM, therapeutic drug monitoring; Cmin, trough concentration.

210 * One patient with two treatment sequences was included in both groups.

211

212 Figure 2. C reactive protein levels in patients who experienced a voriconazole overdose and those

213 who did not.

214 Table

215 Table 1. Link between VRC overdose and potential risk factors.

	Patients with VRC overdose (n = 31)	Patients without overdose (n = 31)	p-value ^b
Demographics			
Male	17 (55)	17 (55)	1.0
Age (years)	61.5 [53.4-67.5]	53.0 [31.3-61.6]	0.006
Weight (kg)	70.3 [57.3-76.5]	65.0 [53.2-78.2]	0.7
Underlying disease			
Acute myeloid leukemia	20 (64)	26 (84)	0.1
Acute lymphoid leukemia	3 (10)	2 (6)	
Lymphoma	3 (10)	3 (10)	
Others ^a	5 (16)	0 (0)	
Hematopoietic stem cell allograft			
Yes	10 (32)	23 (74)	0.002
Voriconazole treatment			
Voriconazole dose (mg/day)	400 [400.0-557.0]	400 [400.0-500]	0.6
Oral administration (%)	13 [42]	25 [81]	0.002
Voriconazole Cmin (mg/l)	5.3 [4.6-6.6]	1.0 [0.4-2.27]	< 0.0001
Hepatic function			
Bilirubin (mg/l)	12.0 [9.0-22.0]	7.0 [4.25-15.75]	0.02
ALAT (UI/l)	24.0 [11.1-102.2]	36.0 [20.0-49.0]	0.09
Inflammation markers			
CRP (mg/l)	188 (109-227.5)	37 (13.2-83.0)	< 0.0001
Class of CRP levels			
≤ 96 mg/l	25 (81)	5 (16)	< 0.0001
> 96mg/l	6 (19)	26 (84)	
Pump proton inhibitor cotreatment			
Absence	6 (19)	11 (35)	0.4
CYP450 genotypes			
Presence of CYP3A4*22 allele ^c	4 (13)	6 (19)	0.7
Presence of CYP3A5*1 allele ^c	2 (6)	6 (19)	0.3
CYP2C19 phenotype ^d			0.07
Intermediate metabolizer	6 (19)	10 (32)	
Extensive metabolizer	19 (62)	10 (32)	
Rapid metabolizer	6 (19)	11 (36)	
Combined genetic score ^e	2.0 [2.0-2.0]	2.0 [1.6-2.5]	0.7
Group of combined genetic score ^e			0.6
<2	7 (23)	8 (26)	
2	18 (58)	14 (45)	
>2	6 (19)	9 (29)	

Data are presented as n (%) or median (25th-75th percentiles).

^aothers included idiopathic aplasia, myelodysplasia, and myeloma.

^bvalues shown in bold indicate significance.

^cThese alleles were heterozygous for all patients of this cohort, except for two patients who did not experience a VRC overdose, who had two alleles *1 for CYP3A5.

^dbased on the classification proposed by Moriyama *et al.* (21). Based on these guidelines, patients with CYP2C419*2/*17 (one patient in the group of VRC overdose and two patients in the control group) were considered to be intermediate metabolizers. See supplemental data for a detailed description of the CYP2C19 diplotypes (Table E1).

^ebased on our previous studies (11).

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References

1. van de Peppel RJ, von dem Borne PA, le Cessie S, de Boer MGJ. 2017. A new time-dependent approach for assessment of the impact of invasive aspergillosis shows effect on short- but not on long-term survival of patients with AML or high-risk MDS. *Bone Marrow Transplant* 52:883–888. <http://doi.org/10.1038/bmt.2017.71>.
2. Ashbee HR, Barnes RA, Johnson EM, Richardson MD, Gorton R, Hope WW. 2014. Therapeutic drug monitoring (TDM) of antifungal agents: guidelines from the British Society for Medical Mycology. *J Antimicrob Chemother* 69:1162–76. <http://doi.org/10.1093/jac/dkt508>.
3. Schelenz S, Barnes RA, Barton RC, Cleverley JR, Lucas SB, Kibbler CC, Denning DW. 2015. British Society for Medical Mycology best practice recommendations for the diagnosis of serious fungal diseases. *Lancet Infect Dis* 15:461–474. [http://doi.org/10.1016/S1473-3099\(15\)70006-X](http://doi.org/10.1016/S1473-3099(15)70006-X).
4. Dolton MJ, McLachlan AJ. 2014. Voriconazole pharmacokinetics and exposure-response relationships: assessing the links between exposure, efficacy and toxicity. *Int J Antimicrob Agents* 44:183-93. <http://doi.org/10.1016/j.ijantimicag.2014.05.019>.
5. Stelzer D, Weber A, Ihle F, Matthes S, Ceelen F, Zimmermann G, Kneidinger N, Schramm R, Winter H, Zoller M, Vogeser M, Behr J, Neurohr C. 2017. Comparing Azole Plasma Trough Levels in Lung Transplant Recipients. *Ther Drug Monit* 39:93–101. <http://doi.org/10.1097/FTD.0000000000000371>.
6. Li Z, Peng F, Yan M, Liang W, Liu X, Wu Y, Lin X, Tan S, Wang F, Xu P, Fang P, Liu Y, Xiang D, Zhang B. 2017. Impact of CYP2C19 Genotype and Liver Function on Voriconazole Pharmacokinetics in Renal Transplant Recipients. *Ther Drug Monit* 39:422-428. <http://doi.org/10.1097/FTD.0000000000000425>.
7. Hashemizadeh Z, Badiie P, Malekhoseini SA, Raeisi Shahraki H, Geramizadeh B, Montaseri H.

- 241 2017. Observational study of associations between voriconazole therapeutic drug monitoring,
242 toxicity, and outcome in liver transplant patients. *Antimicrob Agents Chemother* (in press)
243 <http://doi.org/10.1128/AAC.01211-17>.
- 244 8. Lamoureux F, Duflot T, Woillard J-B, Metsu D, Pereira T, Compagnon P, Morisse-Pradier H, El
245 Kholy M, Thiberville L, Stojanova J, Thuillez C. 2016. Impact of CYP2C19 genetic
246 polymorphisms on voriconazole dosing and exposure in adult patients with invasive fungal
247 infections. *Int J Antimicrob Agents* 47:124–31.
248 <http://doi.org/10.1016/j.ijantimicag.2015.12.003>.
- 249 9. Hassan A, Burhenne J, Riedel K-D, Weiss J, Mikus G, Haefeli WE, Czock D. 2011. Modulators of
250 Very Low Voriconazole Concentrations in Routine Therapeutic Drug Monitoring. *Ther Drug*
251 *Monit* 33:86–93. <http://doi.org/10.1097/FTD.0b013e31820530cd>.
- 252 10. Hamadeh IS, Klinker KP, Borgert SJ, Richards AI, Li W, Mangal N, Hiemenz JW, Schmidt S,
253 Langae TY, Peloquin CA, Johnson JA, Cavallari LH. 2017. Impact of the CYP2C19 genotype on
254 voriconazole exposure in adults with invasive fungal infections. *Pharmacogenet Genomics*
255 27:190–196. <http://doi.org/10.1097/FPC.0000000000000277>.
- 256 11. Gautier-Veyret E, Fonrose X, Tonini J, Thiebaut-Bertrand A, Bartoli M, Quesada J-L, Bulabois C-
257 E, Cahn J-Y, Stanke-Labesque F. 2015. Variability of voriconazole plasma concentrations after
258 allogeneic hematopoietic stem cell transplantation: impact of cytochrome p450
259 polymorphisms and comedications on initial and subsequent trough levels. *Antimicrob Agents*
260 *Chemother* 59:2305–14. <http://doi.org/10.1128/AAC.04838-14>.
- 261 12. Dolton MJ, Ray JE, Chen SC-A, Ng K, Pont LG, McLachlan AJ. 2012. Multicenter Study of
262 Voriconazole Pharmacokinetics and Therapeutic Drug Monitoring. *Antimicrob Agents*
263 *Chemother* 56:4793–4799. <http://doi.org/10.1128/AAC.00626-12>.
- 264 13. Dolton MJ, Ray JE, Chen SC-A, Ng K, Pont LG, McLachlan AJ. 2012. Multicenter Study of

Voriconazole Pharmacokinetics and Therapeutic Drug Monitoring. *Antimicrob Agents Chemother* 56:4793–4799. <http://doi.org/10.1128/AAC.00626-12>.

14. Li X, Yu C, Wang T, Chen K, Zhai S, Tang H. 2016. Effect of cytochrome P450 2C19 polymorphisms on the clinical outcomes of voriconazole: a systematic review and meta-analysis. *Eur J Clin Pharmacol* 72:1185–1193. <http://doi.org/10.1007/s00228-016-2089-y>.

15. Veringa A, ter Avest M, Span LFR, van den Heuvel ER, Touw DJ, Zijlstra JG, Kosterink JGW, van der Werf TS, Alffenaar J-WC. 2017. Voriconazole metabolism is influenced by severe inflammation: a prospective study. *J Antimicrob Chemother* 72:261–267. <http://doi.org/10.1093/jac/dkw349>.

16. Gautier-Veyret E, Bailly S, Fonrose X, Tonini J, Chevalier S, Thiebaut-Bertrand A, Stanke-Labesque F. 2017. Pharmacogenetics may influence the impact of inflammation on voriconazole trough concentrations. *Pharmacogenomics* 18:1119–1123. <http://doi.org/10.2217/pgs-2017-0054>.

17. Akasaka T, Sueta D, Arima Y, Tabata N, Takashio S, Izumiya Y, Yamamoto E, Tsujita K, Kojima S, Kaikita K, Kajiwara A, Morita K, Oniki K, Saruwatari J, Nakagawa K, Hokimoto S. 2017. CYP2C19 variants and epoxyeicosatrienoic acids in patients with microvascular angina. *IJC Hear Vasc* 15:15–20. <http://doi.org/10.1016/j.ijcha.2017.03.001>.

18. Akasaka T, Hokimoto S, Sueta D, Tabata N, Sakamoto K, Yamamoto E, Yamamuro M, Tsujita K, Kojima S, Kaikita K, Kajiwara A, Morita K, Oniki K, Saruwatari J, Nakagawa K, Ogata Y, Ogawa H. 2016. Sex differences in the impact of CYP2C19 polymorphisms and low-grade inflammation on coronary microvascular disorder. *Am J Physiol - Hear Circ Physiol* 310:1494–1500. <http://doi.org/10.1152/ajpheart.00911.2015>.

19. Bertrand-thiébaud C, Berrahmoune H, Thompson A, Marie B, Drosch S, Siest G, Foernzler D, Visvikis-siest S. 2008. Genetic polymorphism of CYP2C19 gene in the stanislas cohort. A link

with inflammation. *Ann Hum Genet* 72:178–183. <http://doi.org/10.1111/j.1469-1809.2007.00417.x>.

20. Jourdil J-F, Tonini J, Stanke-Labesque F. 2013. Simultaneous quantitation of azole antifungals, antibiotics, imatinib, and raltegravir in human plasma by two-dimensional high-performance liquid chromatography-tandem mass spectrometry. *J Chromatogr B Analyt Technol Biomed Life Sci* 919–920:1–9. <http://doi.org/10.1016/j.jchromb.2012.12.028>.

21. Moriyama B, Obeng AO, Barbarino J, Penzak SR, Henning SA, Scott SA, Agúndez JAG, Wingard JR, McLeod HL, Klein TE, Cross SJ, Caudle KE, Walsh TJ. 2017. Clinical Pharmacogenetics Implementation Consortium (CPIC) Guidelines for CYP2C19 and Voriconazole Therapy. *Clin Pharmacol Ther* 102:45–51. <http://doi.org/10.1002/cpt.583>.

22. Gautier-Veyret E, Fonrose X, Stanke-Labesque F. 2017. Pharmacogenetics of voriconazole: CYP2C19 but also CYP3A4 need to be genotyped. *Clin Pharmacol Ther* <http://doi.org/10.1002/cpt.662>.

23. Rodriguez S, Gaunt TR, Day INM. 2009. Hardy-Weinberg equilibrium testing of biological ascertainment for Mendelian randomization studies. *Am J Epidemiol* 169:505–514. <http://doi.org/10.1093/aje/kwn359>.

24. Roques M, Chretien ML, Favennec C, Lafon I, Ferrant E, legouge C, Plocque A, Golfier C, Duvillard L, Amoureux L, Bastie JN, Maurin-Bernier L, Dalle F, Caillot D. 2016. Evolution of procalcitonin, C-reactive protein and fibrinogen levels in neutropenic leukaemia patients with invasive pulmonary aspergillosis or mucormycosis. *Mycoses* 59:383–390. <http://doi.org/10.1111/myc.12487>.

25. Chai LYA, Netea MG, Teerenstra S, Earnest A, Vonk AG, Schlamm HT, Herbrecht R, Troke PF, Kullberg B. 2010. Early Proinflammatory Cytokines and C-Reactive Protein Trends as Predictors of Outcome in Invasive Aspergillosis. *J Infect Dis* 202:1454–1462.

<http://doi.org/10.1086/656527>.

26. Ventura MAE, Van Wanrooy MJP, Span LFR, Rodgers MGG, Van Den Heuvel ER, Uges DRA, Van Der Werf TS, Kosterink JGW, Alffenaar JWC. 2016. Longitudinal analysis of the effect of inflammation on voriconazole trough concentrations. *Antimicrob Agents Chemother* 60:2727–2731. <http://doi.org/10.1128/AAC.02830-15>.
27. van Wanrooy MJP, Span LFR, Rodgers MGG, van den Heuvel ER, Uges DRA, van der Werf TS, Kosterink JGW, Alffenaar J-WWC. 2014. Inflammation is associated with voriconazole trough concentrations. *Antimicrob Agents Chemother* 58:7098-101. <http://doi.org/10.1128/AAC.03820-14>.
28. Naito T, Yamada T, Mino Y, Kawakami J. 2015. Impact of inflammation and concomitant glucocorticoid administration on plasma concentration of triazole antifungals in immunocompromised patients. *Clin Chim Acta* 441:127–132. <http://doi.org/10.1016/j.cca.2014.12.024>.
29. Shah RR, Smith RL. 2015. Inflammation-induced phenoconversion of polymorphic drug metabolizing enzymes: Hypothesis with implications for personalized medicine. *Drug Metab Dispos* 43:400–410. <http://doi.org/10.1124/dmd.114.061093>.
30. Berge M, Guillemain R, Trégouet D a, Amrein C, Boussaud V, Chevalier P, Lillo-Lelouet A, Le Beller C, Laurent-Puig P, Beaune PH, Billaud EM, Lorient M-A. 2011. Effect of cytochrome P450 2C19 genotype on voriconazole exposure in cystic fibrosis lung transplant patients. *Eur J Clin Pharmacol* 67:253–60. <http://doi.org/10.1007/s00228-010-0914-2>.
31. Wang T, Zhu H, Sun J, Cheng X, Xie J, Dong H, Chen L, Wang X, Xing J, Dong Y. 2014. Efficacy and safety of voriconazole and CYP2C19 polymorphism for optimised dosage regimens in patients with invasive fungal infections. *Int J Antimicrob Agents* 44:436-42. <http://doi.org/10.1016/j.ijantimicag.2014.07.013>.

32. Chuwongwattana S, Jantararoungtong T, Chitasombat MN, Puangpetch A, Prommas S, Dilokpattanamongkol P, Watcharananan SP, Sukasem C. 2016. A prospective observational study of CYP2C19 polymorphisms and voriconazole plasma level in adult Thai patients with invasive aspergillosis. *Drug Metab Pharmacokinet* 31:117–122. <http://doi.org/10.1016/j.dmpk.2015.12.005>.
33. Gautier-Veyret E, Fonrose X, Stanke-Labesque F. 2017. Pharmacogenetics of voriconazole: CYP2C19 but also CYP3A4 need to be genotyped. *Clin Pharmacol Ther* 102:189. <http://doi.org/10.1002/cpt.662>.
34. Dufлот T, Schrapp A, Bellien J, Lamoureux F. 2018. Impact of CYP3A4 Genotype on Voriconazole Exposure. *Clin Pharmacol Ther* <http://doi.org/10.1002/cpt.809>.
35. He HR, Sun JY, Ren XD, Wang TT, Zhai YJ, Chen SY, Dong YL, Lu J. 2015. Effects of CYP3A4 polymorphisms on the plasma concentration of voriconazole. *Eur J Clin Microbiol Infect Dis* 34:811–819. <http://doi.org/10.1007/s10096-014-2294-5>.
36. Shao B, Ma Y, Li Q, Wang Y, Zhu Z, Zhao H, Sun J, Dong L, Zhu Y, Zhao N, Qin Y. 2016. Effects of Cytochrome P450 3A4 and non-genetic factors on initial Voriconazole serum trough concentrations in Hematological Patients with different Cytochrome P450 2C19 genotypes. *Xenobiotica* 1–28. <http://doi.org/10.1080/00498254.2016.1271960>.
37. Gautier-Veyret E, Fonrose X, Tonini J, Thiebaut-Bertrand A, Bartoli M, Quesada J-L, Bulabois C-E, Cahn J-Y, Stanke-Labesque F. 2015. Variability of voriconazole plasma concentrations after allogeneic hematopoietic stem cell transplantation: Impact of cytochrome P450 polymorphisms and comedications on initial and subsequent trough levels. *Antimicrob Agents Chemother* 59:2305-14. <http://doi.org/10.1128/AAC.04838-14>.
38. Gautier-Veyret E, Bailly S, Fonrose X, Tonini J, Chevalier S, Thiebaut-Bertrand A, Stanke-Labesque F. 2017. Pharmacogenetics may influence the impact of inflammation on

361 voriconazole trough concentrations. *Pharmacogenomics* 18:1119-1123.
 362 <http://doi.org/10.2217/pgs-2017-0054>.

363 39. Truffot A, Thiebaut-Bertrand A, Chapuis C, Stanke-Labesque F, Gautier-Veyret E. 2018.
 364 Inhibition of Voriconazole Metabolism by Meropenem: A Role for Inflammation? *Clin Infect*
 365 *Dis* 66:1643-1644. <http://doi.org/10.1093/cid/cix1092>.

366 40. Qi F, Zhu L, Li N, Ge T, Xu G, Liao S. 2017. Influence of different proton pump inhibitors on the
 367 pharmacokinetics of voriconazole. *Int J Antimicrob Agents* 49:403–409.
 368 <http://doi.org/10.1016/j.ijantimicag.2016.11.025>.

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Figure 1

Figure 2

Additional data

Table E1. Distribution of CYP2C19 genotypes

Observed CYP2C19 diplotype	Numbers, n (%)			p-value*
	Whole population (n = 62)	Patients with VRC overdose (n = 31)	Patients without VRC overdose (n = 31)	
*1/*17	17	6	11	0.1
*1/*1	29	19	10	
*1/*2	13	5	8	
*2/*17	3	1	2	

* Fischer's exact test for comparison of CYP2C19 diplotypes between patients with or without VRC overdose.

6 Table E2. Distribution of CRP levels according to CYP2C19 phenotype and class of combined genetic
7 score

	Class of CRP levels		P value*
	Class 1 (≤ 96 mg/L)	Class 2 (> 96 mg/l)	
CYP2C19 phenotype ¹			
Intermediate metabolizer	5	8	0.3
Extensive metabolizer	14	15	
Rapid metabolizer	11	6	
Class of combined genetic score ²			
< 2	6	10	0.5
2	15	16	
> 2	9	6	

CRP, C reactive protein.

*Chi² exact test for comparison of classes of CRP levels according to CYP2C19 phenotype and class of combined genetic score

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References

1. Moriyama B, Obeng AO, Barbarino J, et al: Clinical Pharmacogenetics Implementation Consortium (CPIC) Guidelines for CYP2C19 and Voriconazole Therapy. Clin. Pharmacol. Ther. 2017; **102**: 45–51.
2. Gautier-Veyret E, Fonrose X, Tonini J, et al: Variability of voriconazole plasma concentrations after allogeneic hematopoietic stem cell transplantation: impact of cytochrome p450 polymorphisms and comedications on initial and subsequent trough levels. Antimicrob. Agents Chemother. 2015; **59**: 2305–14.

19 Figure E1. C reactive protein levels according to CYP2C19 phenotype (a) and class of combined
20 genetic score (b)

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